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DETERMINATION OF LOCK CAPACITIES USING SIMULATION MODELING

by

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Final Report

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A major portion of the inland waterway system of the United States consists of a series of locks and dams and the navigation pools maintained behind these dams. With this type of waterway, the locks often serve as the major constraint to the growth of waterborne traffic on the waterway system. Thus, the determination of the capacity of a lock, both the physical limit and the economic capacity, is an essential element in the planning and design of a waterway system. In the past several years, computerized simulation models
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20. ABSTRACT (continued)

have effectively been used in determining the physical capacities of locks in the waterway systems and have provided basic information for the analysis of the economic capacities of these locks. An example of the effective use of simulation modeling for this purpose is demonstrated by the analysis of Locks and Dam 26 (L&D 26), Mississippi River at Alton, Illinois, and the proposed replacement alternatives. L&D 26 has become a serious congestion point on the Mississippi River system and because of its strategic location will limit the growth of waterborne commerce on several major connecting waterway systems. Two simulation models, TOWGEN and WATSIM IV, were used conjunctively to analyze the physical capacity of the existing locks using various procedures for locking vessels. The sensitivity of this capacity determination to various factors was evaluated. Then the capacities of the replacement alternatives were determined in a similar manner to allow the selection of those alternatives that would service the projected traffic through the project life. The usefulness of these simulation models has been proven in several similar studies. These models are continuously being improved. Other simulation models and their supporting data bases are being developed under the ongoing Inland Navigation Systems Analysis (INSA) project of the Corps of Engineers.

PREFACE

This report was prepared for presentation at the First International Waterborne Transportation Conference held at Lake Buena Vista, Florida, on 16-18 October 1975. The work described herein was accomplished in support of a supplemental socio-economic analysis of the replacement of Locks and Dam No. 26 (L&D 26) on the Mississippi River at Alton, Illinois. This analysis was used in the preparation of the Design Memorandum No. 11, Formulation Evaluation Report. A more detailed description of the work reported herein is contained as an attachment to Appendix G of the referenced design memorandum. This study provided the basic information for determining the capacity of the L&D Nos. 24, 25, 26, and 27 and the proposed alternative replacement locks for L&D 26. The current report has been prepared for the purpose of presenting how simulation modeling can be used to determine the capacity of a set of locks using the L&D 26 as an example. The basic study was funded by the U. S. Army Engineer District, St. Louis, and was conducted during the period from October 1974 through May 1975. This report was prepared during September through October 1975.

The study was accomplished under the general supervision of Mr. H. B. Simmons, Chief, Hydraulics Laboratory, and Mr. M. B. Boyd, Chief, Mathematical Hydraulics Division. Dr. L. L. Daggett, Mathematical Hydraulics Division, was responsible for the study. Mr. T. D. Ankeny, Mathematical Hydraulics Division, assisted in the study. Mr. Anson Eickhorst, U. S. Army Engineer Division, North Central, and Messrs. Robert Daniels, Richard Mankus, and Brad Fowler, U. S. Army Engineer District, St. Louis, provided special advice and assistance during the study.

Director of WES during the study was COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

DETERMINATION OF LOCK CAPACITIES USING SIMULATION MODELING

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INTRODUCTION

1. The importance of the inland waterway system as an element in the national transportation system has been growing steadily with the percentage of intercity freight in terms of ton-miles being carried by this mode growing from 3.6 percent in 1940 to 11.2 percent in 1972.[1] All of the major navigable waterways connecting to the Lower Mississippi River now consist of a series of locks and dams and the connecting navigation pools created behind these dams. These locks are key elements in allowing the traffic to pass from pool to pool and frequently become the primary points of congestion as the traffic on the waterway increases. When the congestion becomes severe enough, improvements to the locks are required to allow the waterborne commerce to continue to grow.

2. Determining when improvements should be made at various points on the waterway system is a very important decision because the investments required for major improvements to the waterway system are large. The cost of not adequately increasing the capacity of the locks can likewise be very large. Determining when a lock will require improvement (either the replacement or addition of a larger size lock) requires the determination of the lock's capacity. Likewise, designing the replacement or additional structure requires the determination of capacities of the proposed alternative locks to assure that all of the projected traffic can be serviced in an efficient and economical manner.

3. There are basically two types of capacities that can be determined for a given set of locks, an economic and a physical capacity. It may well be possible to physically pass more traffic through a set of locks than would be economically justified, i.e., the replacement of a given set of locks could be economically justified at a level of traffic below the physical limit of traffic for those locks. It was not until recently that systematic methods of determining the physical and practical capacity of locks have been developed and applied.[2,3,4] The use of simulation modeling for this purpose has developed significantly over the past five years. The Corps of Engineers is now regularly using the simulation modeling approach for determining the capacities of locks. A recent application of this method will be presented as

an example of the usefulness and flexibility of this approach. This application involves the proposed replacement of L&D 26 on the Mississippi River.

General Description

4. L&D 26 is located on the Mississippi River at Alton, Illinois, approximately 202.9 mi above the confluence of the Ohio River. The locks became operational in 1938 and consist of a 600-ft x 110-ft landward main chamber adjacent to the Illinois bank and a 360-ft x 110-ft riverward auxiliary chamber. The gated dam extends from the locks to the Missouri bank, providing a slackwater pool for navigation to L&D 25 on the Mississippi River and to LaGrange L&D on the Illinois Waterway. An average lift of 18 ft is maintained between the L&D 26 pool and the pool formed by L&D 27, the last L&D encountered by through traffic heading downstream on the Mississippi.

Problem

5. The rapid increase in river traffic beyond expectation has caused this location to become a "bottleneck" due to the physical limits imposed by the chamber sizes. The volume of traffic passing through L&D 26 has increased in magnitude and has changed composition. Congestion makes the incidence of one and two barge local movements less likely, while the 1200-ft long chamber at L&D 27 helps influence makeup of long distance tows. Tows are made in larger configurations as more powerful towboats become available. These factors cause an increase in the number of double lockages. Compounding the problem are the lack of up-to-date operating equipment to assist in hauling cuts from the chambers, poor alignment of the approaches, and a severe outdraft, which adversely affect the large tows. As the number of tows requiring lockages increases, queues build and delays become excessive.

Purpose of the Study

6. This study was initiated to aid in defining a capacity for the existing locks and to investigate the capacities of replacement alternatives at L&D 26. Capacity as used in this report is the term applied to the amount of tonnage that can be passed through a lock(s) before queues become excessively large and/or the delays become intolerable. It is a physical limit that can be used to compare alternative lock configurations. Throughout this report, "replacement alternatives" is used to define the proposed designs (chamber size and number) and location of new locking facilities.

7. Various chamber sizes and configurations at the present site and for a proposed location downstream, where the approach conditions

would be more favorable, were to be studied. Results of this project were then used in an economic analysis of the present facility and various proposed alternatives.

SIMULATION MODEL USED

Introduction

8. The simulation procedure used involved two steps. The first generated the tows that would require movements through the simulated locks and their characteristics and prepared a tow list to be used as input in the second step. The second step involved modeling these tow movements through the locks and presenting statistics describing the locks' performance which were gathered during these simulated movements. The first step was accomplished using a simulation model program called TOWGEN and the second step used a waterway simulation model--WATSIM IV.

TOWGEN

9. TOWGEN uses the towing fleet characteristics and the origin-destination (O-D) matrix of commodity movements to produce a list of tows. This list is then processed by WATSIM IV and various tables of statistics are produced for the ports, locks, and delay points of the system simulated. Figure 1 presents a generalized logic diagram of TOWGEN.

10. Major TOWGEN input data consist of the following:

a. O-D tonnage matrix by commodity.

b. Barge type data: average loading, commodities carried, and dedicated equipment percentage.

c. Flotilla size vs towboat horsepower frequency distribution by tow type.

d. O-D mileage table and other system description data.

Processing within TOWGEN is accomplished in the following sequence. The commodity O-D matrices are allocated to the various barge types. Then the cumulative tonnage O-D matrix for each barge type is divided through by average barge loadings to produce a matrix of loaded barge O-D movements. Next, the movements of empty barge activity are determined. This is done by (a) providing empty movements of dedicated equipment and (b) eliminating any remaining imbalances between barges originating and terminating at each port by providing empty barge movements which minimize total empty barge-miles of travel. The total barge O-D matrix (loaded plus empty barges) is then divided through by the average flotilla size to determine the O-D tow movements required. This tow O-D matrix is randomly sampled without replacement,

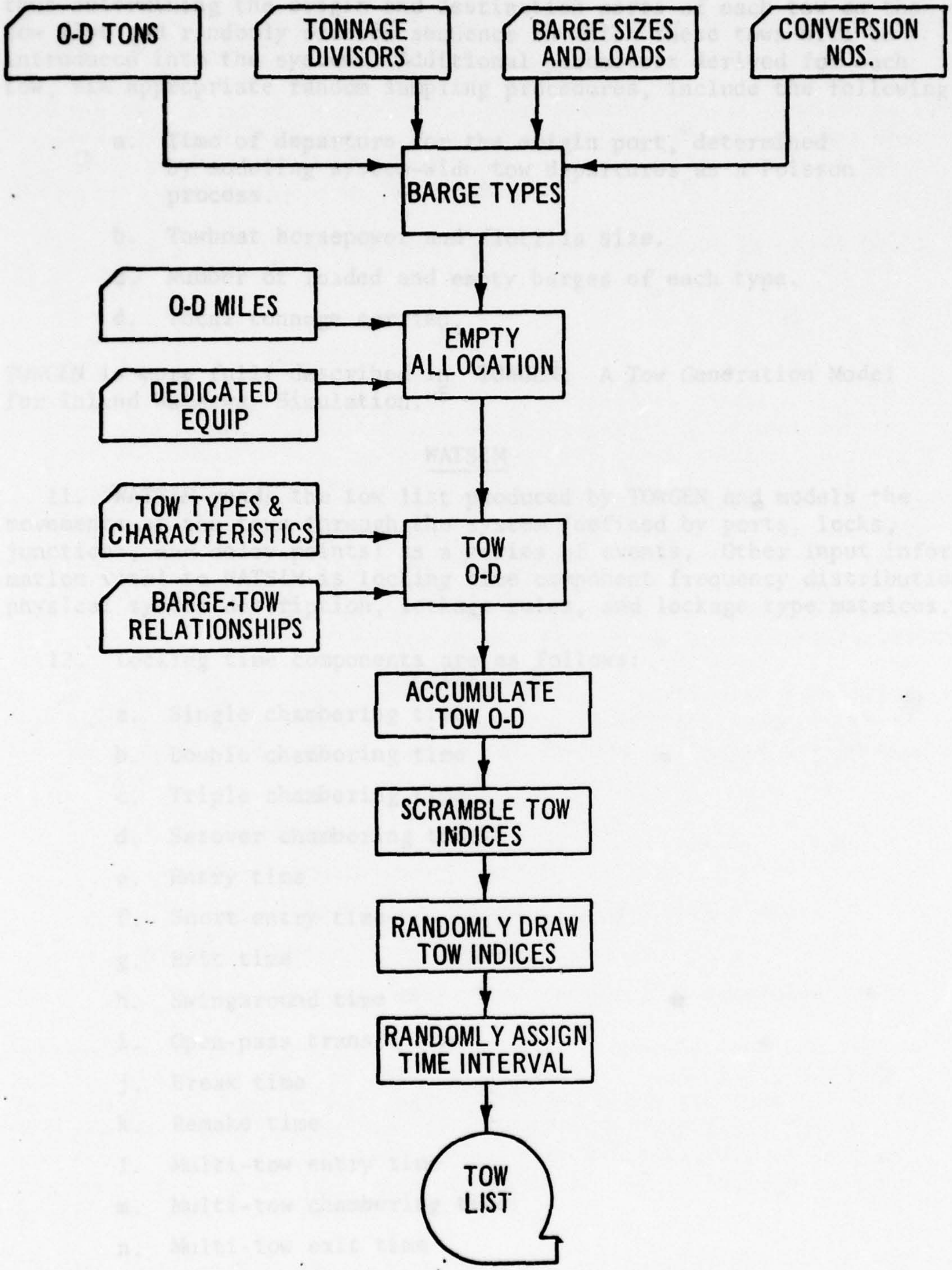

Figure 1. TOWGEN Logical Flow Diagram

thus determining the origin and destination ports of each tow on the tow list and randomly ordered sequence in which these tows will be introduced into the system. Additional parameters derived for each tow, via appropriate random sampling procedures, include the following:

a. Time of departure for the origin port, determined by modeling system-wide tow departures as a Poisson process.

b. Towboat horsepower and flotilla size.

c. Number of loaded and empty barges of each type.

d. Total tonnage carried.

TOWGEN is more fully described in "TOWGEN: A Tow Generation Model for Inland Waterway Simulation."[5]

WATSIM

11. WATSIM reads the tow list produced by TOWGEN and models the movements of the tows through the system (defined by ports, locks, junctions, and delay points) as a series of events. Other input information vital to WATSIM is locking time component frequency distribution, physical system description, lockage rules, and lockage type matrices.

12. Locking time components are as follows:

a. Single chambering time

b. Double chambering time

c. Triple chambering time

d. Setover chambering time

e. Entry time

f. Short entry time

g. Exit time

h. Swingaround time

i. Open-pass transit time

j. Break time

k. Remake time

l. Multi-tow entry time

m. Multi-tow chambering time

n. Multi-tow exit time

All components are separately identified by direction (up and down) except swingaround, open-pass, break, and remake times. These 25 components describe probablistically the time required to perform locking operations at a particular lock chamber. These components are sampled during the simulation process according to lockage type and preceding conditions at the lock using a Monte Carlo procedure to obtain the processing time for a tow.

13. The physical system description is on a point-by-point basis. Points may describe:

a. Ports

b. Locks

c. Channel junctions

d. Delays

Each point is represented by one data card that contains the description of the point and the channel characteristics (width, depth, and flow velocity) for the upstream channel segment. A channel restriction type of delay point is an exception to this rule and requires two data cards, one for the upstream end and another for the downstream end. The downstream card carries the actual restricted channel characteristics.

14. The lockage rules to be used during a particular simulation run may be specified in a set of optional parameters, some of which may be used in combination. Locks can operate using the following procedures:*

a. Strict first in, first out (FIFO)

b. FIFO with multi-tow** option

c. Strict N-up, M-down (NUMD) with variable N and M

d. NUMD with multi-tow option

e. Allow open-pass conditions to occur at scheduled times

An example of the NUMD rule would be when 3 upbound tows are locked consecutively followed by locking 3 downbound tows, i.e., 3U3D. N and M do not have to be equal. If N and M are set equal to 1, this lockage rule will become the "flip-flop" rule that calls for serving the first vessel on each side of the lock alternatively as long as there are vessels on each side of the lock. If no lockage rule is specified, operation defaults to FIFO.

15. Open-pass (transit of a lock without closing the gates and filling or emptying the chamber) conditions are incorporated into the

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* All of these can also operate in a "Ready-to-serve" regime.

** More than one tow per lockage.

operation of a lock on a time history basis. Twenty periods of open-pass can be input per lock. If no open-pass occurs, the time history cards are omitted from the input data. Open-pass can be operated in an NUMD mode. The N and M variables can be different than the N and M values of regular NUMD operation and do not have to be equal to each other. Open-pass conditions may be modeled at locks using locking rules a-d.

16. A "Ready-to-Serve" policy was implemented in WATSIM for this study. Using the basic assumption that the separate units (cuts) of a large tow are locked immediately following one another, the model selects the appropriate entry (long or short) for the first cut, while succeeding cuts have short or turnback entries. A single lockage time is drawn for each cut and a swingaround time is obtained for each chamber reversal between cuts. Only one exit time is drawn for the last cut because the lock can begin the swingaround as soon as the exiting cut's stern crosses the sill. The lockage time for this tow in the ready-to-serve mode is described by Equation (1) where E_1 is the first-cut entry time; S_i is the short entry time of the i^{th} cut; R_i is the swingaround time of the i^{th} cut, X is the exit time; P is the processing time for the tow; and N is the number of cuts required to process the tow.

$$P = E_1 + \sum_{i=1}^{N} C_i + \sum_{i=1}^{N-1} (S_i + R_i) + X \qquad (1)$$

17. With the ready-to-serve policy, if the tow has just arrived and is not required to wait in queue for the lock to be ready, the processing time is increased to reflect the additional time required to break the tow into separate units. The remake time is computed as a delay to the tow and is charged against the lock in the algorithm in WATSIM. Delays for remake time were later removed from the delay time charged to the lock for L&D 26 ready-to-serve runs, since it was considered that this did not allow a valid comparison with the delays to tows computed for the other locking policies. The model includes remake time in accounting for the tow's transit time to the next point on the simulated waterway.

18. The lockage type matrix contains the information that is used to determine the type of lockage a particular tow receives at a lock in the system. This matrix is developed exogenous to the program. Each barge type is considered in a particular configuration, then the configuration is compared to the lock size. This comparison produces a type of lockage, which is coded into the matrix. This matrix is sampled for every tow that traverses a lock to determine the time frequency distribution to be used in simulating the tow's chambering time.

19. WATSIM reads tows from the tow list provided by TOWGEN at the time of entry specified for each tow and moves the tows from origin to destination while it compiles statistical data at the locks, ports, and delay points and for the tows. A simplified logic diagram of WATSIM is shown in Figure 2. This complex operation is controlled by a module in the simulation program called the scheduler. Every event occurs in chronological order with control being transferred to other modules that originate and terminate tows, calculate the lock operations, move tows from point-to-point, and compile statistics as needed by the scheduler. At the end of the simulation time (or intermittently, if desired), the statistics gathered are printed out.

20. WATSIM IV echo-prints all of the input data and prints the tow code deck used by TOWGEN to create the tow list. The data obtained during a WATSIM run are output in 12 tables. The type of output available is indicated by the following list:

a. Numbers of barges and tows of each type originated and terminated at each port.

b. Numbers of tows and barges and total tonnage transiting each lock.

c. Total and average delay and process times at each lock.

d. Maximum delays and queue lengths at locks.

e. Number of lockages and average locking times for each lockage type by lock chamber.

f. Frequency distributions of tow delays and headway spacings.

g. Instantaneous and cumulative inventories of towboat and barge utilization.

h. Summary of system delays.

21. A more detailed description of WATSIM IV may be obtained by referencing "A New Generalized Waterway Simulator: WATSIM IV."[6]

Approach to the Problem

22. The basic problem then was to determine the capacity in terms of the amount of commerce, measured in tons, that can be serviced through the present locks at L&D 26 and the proposed alternative replacements for L&D 26. The capacity level of a set of locks is not a single value but is a stochastic variable which is dependent upon a number of factors. Therefore, a testing program had to be developed to allow the consideration of these factors in the decision of what the limiting capacity of the various locks might be. The stochastic nature of the service demands and times required to process these

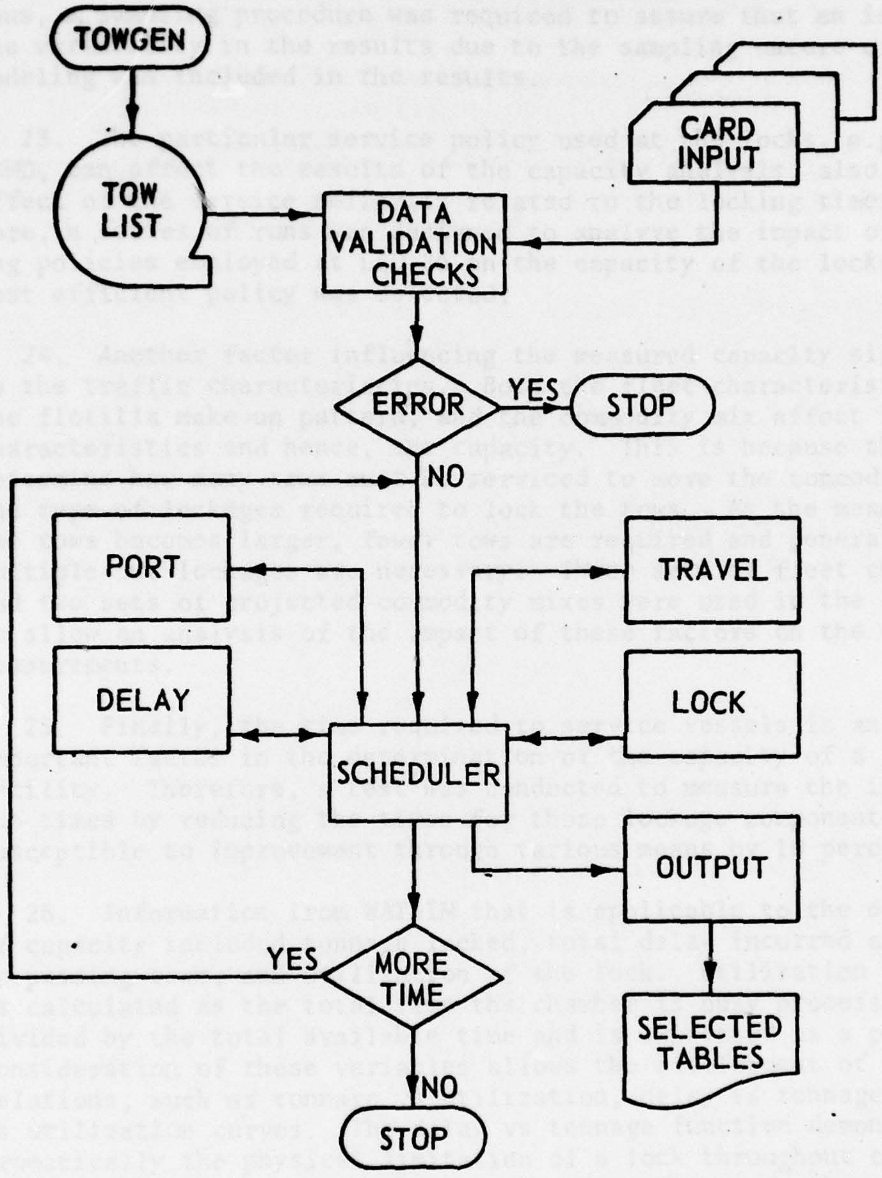

Figure 2. WATSIM Logical Flow Diagram

demands and the event sampling nature of the WATSIM model allowed the measurement of only one of a large number of possible event series. Thus, a sampling procedure was required to assure that an indication of the variability in the results due to the sampling nature of event modeling was included in the results.

23. The particular service policy used at the locks, e.g., FIFO or NUMD, can affect the results of the capacity analysis, also. The effect of the service policy is related to the locking times. Therefore, a series of runs was designed to analyze the impact of the operating policies employed at L&D 26 on the capacity of the locks and the most efficient policy was selected.

24. Another factor influencing the measured capacity significantly is the traffic characteristics. Both the fleet characteristics, i.e., the flotilla make-up pattern, and the commodity mix affect the traffic characteristics and hence, the capacity. This is because these factors determine how many tows must be serviced to move the commodities and the type of lockages required to lock the tows. As the mean size of the tows becomes larger, fewer tows are required and generally more multiple-cut lockages are necessary. Three sets of fleet characteristics and two sets of projected commodity mixes were used in the capacity runs to allow an analysis of the impact of these factors on the capacity measurements.

25. Finally, the time required to service vessels is another important factor in the determination of the capacity of a lock facility. Therefore, a test was conducted to measure the impact of the times by reducing the times for those lockage components most susceptible to improvement through various means by 10 percent.

26. Information from WATSIM that is applicable to the determination of capacity included tonnage locked, total delay incurred at the lock by passing tows, and utilization of the lock. Utilization of the lock is calculated as the total time the chamber is busy processing tows divided by the total available time and is expressed as a percentage. Consideration of these variables allows the development of functional relations, such as tonnage vs utilization, delay vs tonnage, and delay vs utilization curves. The delay vs tonnage function demonstrates dramatically the physical limitation of a lock throughput capability as the function reaches an asymtotic value of tonnage when critical delay values are experienced. The tonnage vs utilization function is linear for most cases and gives a good estimate of utilization for particular levels of tonnage under a given set of assumptions about the traffic characteristics.

27. The various lock designs tested were:

a. L&D 26 Present Locks (600 ft x 110 ft; 360 ft x 110 ft)

b. L&D 26 Present Site; Replacement Locks (1200 ft x 110 ft; 600 ft x 110 ft)

c. L&D 26 New Site; Replacement Locks (1200 ft x 110 ft; 600 ft x 110 ft)

d. L&D 26 New Site; Single Lock (1200 ft x 110 ft)

e. L&D 26 New Site; Dual Locks (1200 ft x 110 ft; 1200 ft x 110 ft)

28. For the simulation, these various "locks" were placed between two ports from which all tonnage movements originated and terminated. For L&D 26, these two ports represent points in the L&D 26 pool and the L&D 27 pool near the lock through which all tows passing must arrive and depart. Simulation runs were of 30-days duration with output generated at 6-day intervals. These five samples per run were then extrapolated to annual values. The annual values for the curves desired were then plotted. An exponential function was determined for the delay vs tonnage curve and a linear function was determined for the tonnage-utilization data by a least squares fit.

Model Data

29. TOWGEN produces a tow list from the fleet characteristics and the commodity tonnage. Fleet characteristics were obtained from an analysis of data collected during August 1972 at L&D 26. The data available for each tow locked consisted of number of barges, tow horsepower, commodity carried, and tonnage. If more than one commodity was carried in the tow, the commodity was identified as mixed.

30. Because the type of equipment used to carry the various commodities affects the tow sizes so greatly, the data were separated by commodity into four groups: dry cargo, petroleum, chemicals and sulphur.* Barge sizes vary and because this size is quite important in determining the number of tows required to move the commodities and the type of lockage required, it was important to determine the barge sizes included in each tow. Therefore, the number of loaded barges was divided into the tonnage carried by each tow to obtain an average tonnage per barge. This average was then used in determining the size of barges in the tow. This required an assumption that barges of various sizes were not mixed in a given tow. This has been observed to be true in most cases. From a simple displacement calculation, a tonnage range for various barge sizes was found. Use of this range of

*Sulphur was later combined with chemicals because of the limited sample size and because the characteristics of the equipment used to carry these commodities are similar.

average barge loadings for various size barges allowed the classification of the sample data into several barge size groupings. Based upon this analysis, the commodities were assigned to be carried in the barge types used in the modeling studies. Dry commodities were assigned to 195-ft x 35-ft jumbo hopper barges. Three predominate barge sizes were observed for petroleum and liquid chemicals and, therefore, these commodities were carried in 195-ft x 35-ft; 240-ft x 50-ft; and 290-ft x 50-ft tank barges in the simulation. The assignment of the commodities to the barge types used to haul the commodity is shown in Table 1.

31. A frequency distribution of tow size (number of barges) vs horsepower was now developed from the L&D 26 traffic analysis printouts furnished by the St. Louis District. This set of fleet characteristics was considered representative of the tow mix through L&D 26 in 1972 and through the remainder of this report is referred to as "1972 Traffic Characteristics" and "Current Fleet." Table 2 presents the average size tow for the 1972 fleet obtained from this analysis and used in the model study.

32. It has been observed in the past that the average number of barges carried in a tow; hence, the tow size through L&D 26 has been increasing steadily at a rate of about one barge per decade. The average load per tow has also been increasing steadily. Therefore, a second set of fleet characteristics was derived using the 1972 fleet as a base and increasing the average tow size so that the 600-ft x 110-ft chamber would be "full" or more nearly so for each lockage. In other words, the lock would have more barges per lockage to obtain an optimum amount of tonnage per lockage. This set is referred to as "Large Tow Characteristics" and Table 2 presents the average tow characteristics of this fleet also. Since changes in equipment operating on the waterway are gradual, this set will not be applicable until sometime in the future. Whether the observed rate will continue is subject to question and depends largely on the equipment availability, company operating policies, communications facilities, rate structure and Federal policies, and availability of commodities and loading facilities. Because a major change in fleet characteristics is not likely in the near future, a third set of fleet characteristics involving a much less drastic shift in average tow sizes from the 1972 characteristics was developed and is called "Intermediate Fleet Characteristics." This fleet's average size is shown in Table 2.

33. After determining the fleet characteristics, the next task was the development of the locking time component frequency distributions to be used in determining the service time required for locking tows in the model. This was a very difficult task because the sources of data did not use the same definitions of the locking components to collect data, the data sample sizes were too small or the data were unavailable. Two basic sources of data were available for use; one was the data collected routinely at L&D 26 and the second was the data

TABLE 1

Commodity Assignment to Barge Types (%)

Commodity	Hopper	Petroleum Jumbo	Petroleum Tank (Med)	Petroleum Tank (Large)	Chemical Jumbo	Chemical Tank (Med)	Chemical Tank (Large)
Corn	100						
Soybeans	100						
Grain	100						
Coal	100						
Petroleum		13	40	47			
Gravel, Sand & Stone Aggregate	100						
Iron & Steel	100						
Industrial Chemical					40	28	32
Agricultural Chemical					100		
Other & Miscellaneous	100						

TABLE 2

Tow Characteristics

Tow Type	Avg Load/ Barge (tons)	Avg H.P/Tow	1972 Fleet Avg Barge/Tow	Intermediate Fleet Avg Barge/Tow	Large Fleet Avg Barge/Tow
Hopper	1314	2065	7.54	7.75	10.60
Petroleum Jumbo	1400	2650	4.70	5.58	7.54
Petroleum Tank (Med)	2460	2650	3.88	4.09	6.69
Petroleum Tank (Large)	2973	2650	3.19	3.19	4.69
Chemical Jumbo	1400	2545	6.56	6.60	10.27
Chemical Tank (Med)	2460	2545	3.09	3.55	5.74
Chemical Jumbo (Large)	2973	2545	2.92	3.08	4.74

collected by Peat, Marwick, Mitchell and Company (PMM&C) during a series of tests conducted in 1974 to determine the effectiveness of employing helper boats at L&D 26. PMM&C made these data available for use in this study. Very little data were available on locking times in the auxiliary chamber and what data were available were heavily affected by the large number of lockages that involved power units with no barges and pleasure craft. These vessels usually require much less time to maneuver into and out of the lock chambers and can wait much closer to the lock entrance. Thus, great care and judgment were required in determining the locking times used in this study. This was one of the factors that made the sensitivity test of capacity to the lockage times important.

34. For L&D 26, the data obtained by PMM&C were the source of most of the data. There were two data collection periods: the base data collection period of 10-19 November 1973 and the switchboat test data collection period of 19 November-19 December 1973. The main chamber time frequency distributions of the single, double, and knockout chambering times, the long and short entry times, and the swingaround times were derived from these data. The main chamber exit time frequency distributions were obtained from the PMM&C data by adjusting the recorded times to allow for a difference in definitions of when the exit begins. The simulation model begins the exit time when the tow's stern crosses the exiting sill while the PMM&C definition of exit begins when the gates are fully open. Thus, the PMM&C times had to be reduced to remove the recoupling time for multicut lockages and the chamber exit time. The chambering times for doubles and knockouts had to be adjusted for these factors also. The PMM&C data were also the source of the tow breakdown and remake time distributions used during the ready-to-serve operations. These times for the 600-ft x 110-ft locks were used for the present locks and the present site 1200-ft and 600-ft tests. The tests with the new site 1200-ft and 600-ft chambers used these distributions with the long entry time adjusted to reflect the improved approach channel conditions.

35. The auxiliary chamber (360-ft x 110-ft) times were not as readily available. The PMM&C data collection did not involve collecting times for the auxiliary chamber. The normal L&D 26 times for chambering were available as a mean monthly value but were not separately identified by direction. There were no exit times recorded and the data were heavily influenced by the inclusion of large numbers of small tows and pleasure craft. The time frequencies for the auxiliary chamber were obtained by adjusting the distributions of the main chamber so that these distributions would have a mean value that corresponded to the long-term averages of the lockage components obtained from the normal L&D 26 data collection procedure for the period--January 1972 to October 1974. The exit time distributions for the main chamber were used for the auxiliary chamber also.

36. Because there is no 1200-ft x 110-ft chamber at L&D 26, the data for the time distributions associated with this chamber had to be obtained from similar chambers in existence for which data were available. Distributions for the replacement main chamber (1200-ft x 110-ft) were derived from an analysis of four locks (Pike Island, New Cumberland, Racine, and Belleville) on the Ohio River during 1968. These locks have average lifts ranging from 17.8 ft to 21.0 ft and also have favorable approach conditions. The tow break and remake times for the present 600-ft x 110-ft chamber were used here also. The time distributions for this chamber (1200-ft x 110-ft) were used at the new site for simulation of new site: single chamber, dual chambers, and replacement chambers. When the 1200-ft x 110-ft lock was simulated at the present site, the long entry of the present main chamber was used to reflect the existing approach conditions at the present site. When the 600-ft x 110-ft chamber was used at the new site, the long entry of the 1200-ft x 110-ft distribution was used to simulate more favorable approach conditions.

37. The definition of capacity at L&D 26 was determined from a simple simulation system setup. The simulation system was composed of two ports with a lock facility between them as discussed above. This setup allowed more efficient execution of the simulation runs.

38. The averages of these distributions for all of these cases are displayed in Table 3.

Verification Data

39. For any simulation, it is important to verify the results obtained with "real world" values. The process of comparison and model adjustment is called verification. Prototype data from L&D 26 were taken for the month of August 1972. The information available by chamber included: total tows, number of loaded and empty barges, tonnage, number of lockages by type, and utilization. Similar data were extracted from data taken over a 3-year period (1972-1974). Refer to Tables 4 and 5 for the values used for verification. An average delay experienced at the lock was also obtained for August 1972.

Verification Results

40. The simulation was run for a typical 30-day month. Values from the output tables were then compared with the prototype data discussed above. Two comparisons can be made. One can look at the

TABLE 3

Average Times of Lockage Components at L&D 26 (min)

	360'x110'			600'x110'			1200'x110'	
	Present Site							
		Helper Boat	Large Fleet		Helper Boat	New Site	Present Site	New Site
Single Up	15	15	19	24	24	24	22	22
Dn	15	15	20	24	24	24	22	22
Double Up	70	61	70	97	62	97	70	70
Dn	71	64	71	103	62	103	70	70
Triple Up	123	123	123	157	157	157	0	0
Dn	123	123	123	157	157	157	0	0
Setover Up	62	62	62	46	46	46	0	0
Dn	62	62	62	46	46	46	0	0
Long Entry Up	19	19	19	20	20	13	20	13
Dn	18	18	18	21	21	12	21	12
Short Entry Up	3	3	3	3	3	3	4	4
Dn	3	3	3	3	3	3	4	4
Exit Up	8	8	8	8	8	8	9	9
Dn	8	8	8	8	8	8	8	8
Swingaround	13	13	13	13	13	13	19	19
Break	6	6	6	6	6	6	6	6
Remake	14	14	14	14	14	14	14	14
Multivessel-Up							11	11
Entry Dn							10	10
Multivessel-Up							22	22
Lockage Dn							22	22
Multivessel-Up							4	4
Exit Dn							4	4

TABLE 4
LOCKS AND DAM 26 VERIFICATION
Comparison of Results by Chamber

	Verification Run 30-days	'72-'74 Avg. Month	Difference %	Verification Run* 31-days	August 1972	Difference %
Main Chamber						
Total Tows	453	431	+5	469	468	0
Singles	83 (18%)	77 (18%)	0	68 (18%)	68 (15%)	+3
Doubles	262 (58%)	233 (54%)	+4	271 (58%)	260 (56%)	+2
Setovers	106 (23%)	121 (28%)	-5	110 (23%)	140 (30%)	-7
Triples	2 (0%)	0 (0%)	0	2 (0%)	0 (0%)	0
Total Barges	3907			4037		
Utilization	96.71%			96.7%	91.4%	+5
Aux Chamber						
Total Tows	350	332	+5	361	380	-5
Singles	149 (43%)	220 (66%)	-23	154 (43%)	213 (56%)	-13
Doubles	155 (44%)	51 (15%)	+29	160 (44%)	98 (26%)	+18
Setovers	32 (9%)	54 (16%)	- 7	33 (9%)	62 (16%)	- 7
Triples	14 (4%)	7 (2%)	+ 2	14 (4%)	7 (2%)	0
Total Barges	1236			1277		
Utilization	56.08%			56.1%	48.9%	+7

*Adjusted from 30-day values.

TABLE 5

LOCKS AND DAM 26 VERIFICATION
Comparison of Total Results for Locks

Lock	Verification Run 30 days	'72-'74 Avg Month	Difference %	Verification Run* 31-days	August 1972	Difference %	August 1972 Adj.†	Difference %
Total Tows	803	763	+ 5	830	848	- 2	781	+6
Singles	232 (29%)	297 (39%)	-10	240 (29%)	281 (33%)	- 4	214 (27%)	+2
Doubles	417 (52%)	284 (37%)	+15	431 (52%)	358 (42%)	+10	358 (46%)	+6
Setovers	138 (17%)	175 (23%)	- 6	143 (17%)	202 (24%)	- 7	202 (26%)	-9
Triples	16 (2%)	7 (1%)	+ 1	16 (2%)	7 (1%)	1	7 (1%)	+1
Loaded Barges	3371			3483	3448			
Empty Barges	1772 (34%)	(34%)	0	1831 (34%)	1676 (33%)	+ 1		
Utilization	76.40%			76.4%				
Total Ktons	4940.34	5040	- 2	5105.02	5158	- 1		
Avg. Wait (D)	358			358				
Avg. Wait (All)	306			306	319**	- 4		
Ktons/tow	6.15			6.15	6.08	+ 1	6.60	-7
Bgs/tow	6.40			6.40	6.04	+ 6	6.56	-2

* Adjusted from 30-day values.

† Light boats adjusted from data.

** 319 min. was the average waiting time for tows passing through the main chamber of L&D 26. The vessels passing through the auxiliary chamber averages 53-min waiting time. However, the time of arrival for pleasure craft and power units only are not recorded and, therefore, no wait time for these vessels can be determined.

simulation month and the average month for the 3-year period or the simulation results can be adjusted* and compared with August 1972. A careful look at Tables 4 and 5 reveals that the model results compare favorably with the prototype data from both sources.

41. The primary measure of good modeling results is the reproduction of the number of observed tows, tonnage, ratios of lockage types, and percent dedicated equipment. As can be observed, the total number of tows serviced by the model during the sampling period is closely reproduced, within 5 percent. Likewise, the total tonnage passing through the locks was reproduced within 2 percent. The ratio of lockage types occurring at the lock seem to have a rather large error. The results for the main chamber are quite accurate, being within 5 to 7 percent. The large errors occur in the lockage type ratios of the auxiliary chamber. The number of single lockages produced in the model are significantly underestimated in this chamber and the double lockages are overestimated. This can be explained largely by the fact that the model does not handle pleasure craft and power unit only vessels; therefore, eliminating many single lockages. The percent utilization is reproduced within 5 to 7 percent. The percent empty barges is within 1 percent and the average waiting time is within 4 percent of the observed values at the lock.

42. After comparison, the model can be adjusted to produce results closer to prototype by the insertion of several factors. No adjustments were required. The results of simulation produced differences of less than 10 percent on the average. This gives an indication of reliability in testing alternatives to the present locks.

Method for Determining Capacity

43. As mentioned briefly in the preceding section (Approach to the Problem), there were two methods used to determine capacity for this project. One approach was to analyze delay time as a function of tonnage and the second method determined utilization of the lock as a function of tonnage. The analysis involved plotting the experimentally determined values and fitting functions or curves to these data points using the least squares method. The plots are on an annual basis of delay time and tonnage with utilization ranging from 0 to 100 percent. Annual values were derived by multiplying the monthly sample values by the ratio used to obtain the monthly tonnage levels; i.e., 10.5. Figures 3 and 4 are examples of these two types of plots. One can observe that an envelope of uncertainty can be placed around these curves and a range of "capacity values" found.

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*Values adjusted to reflect 31-day month.

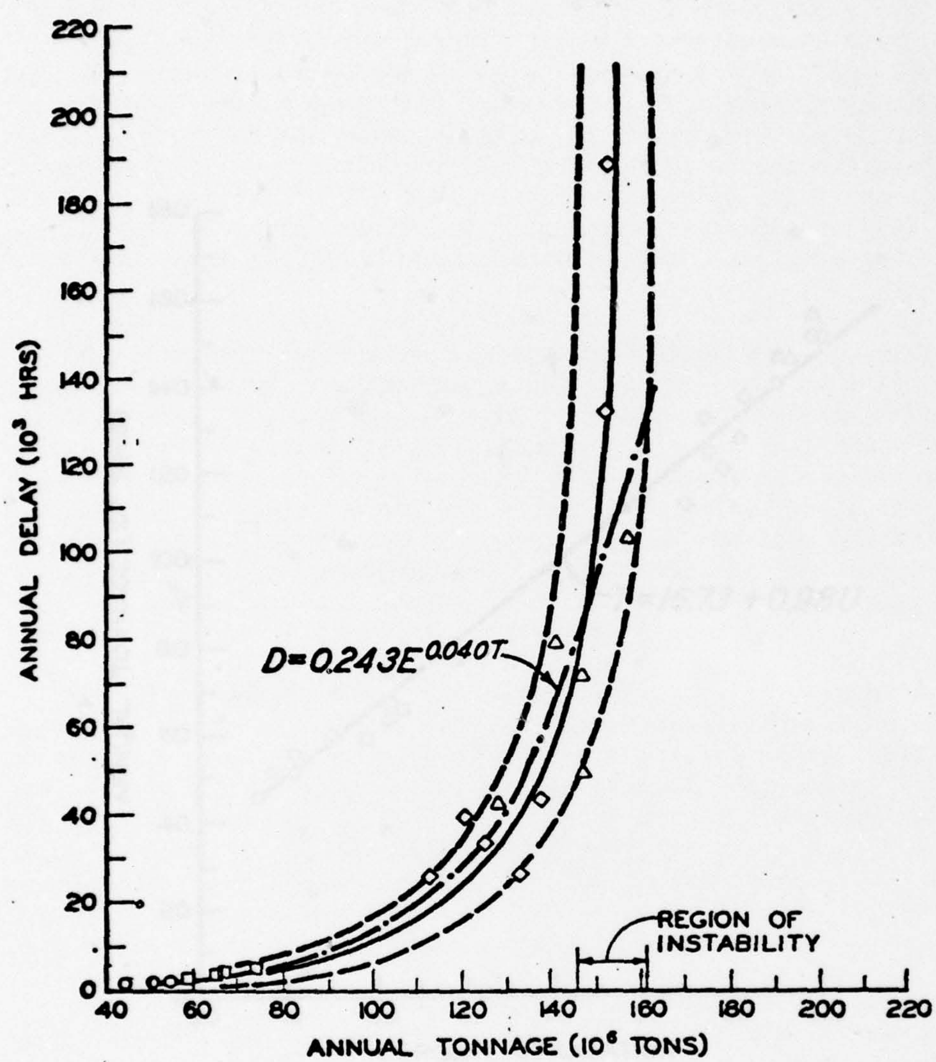


Figure 3. Example of Annual Delay vs Annual Tonnage

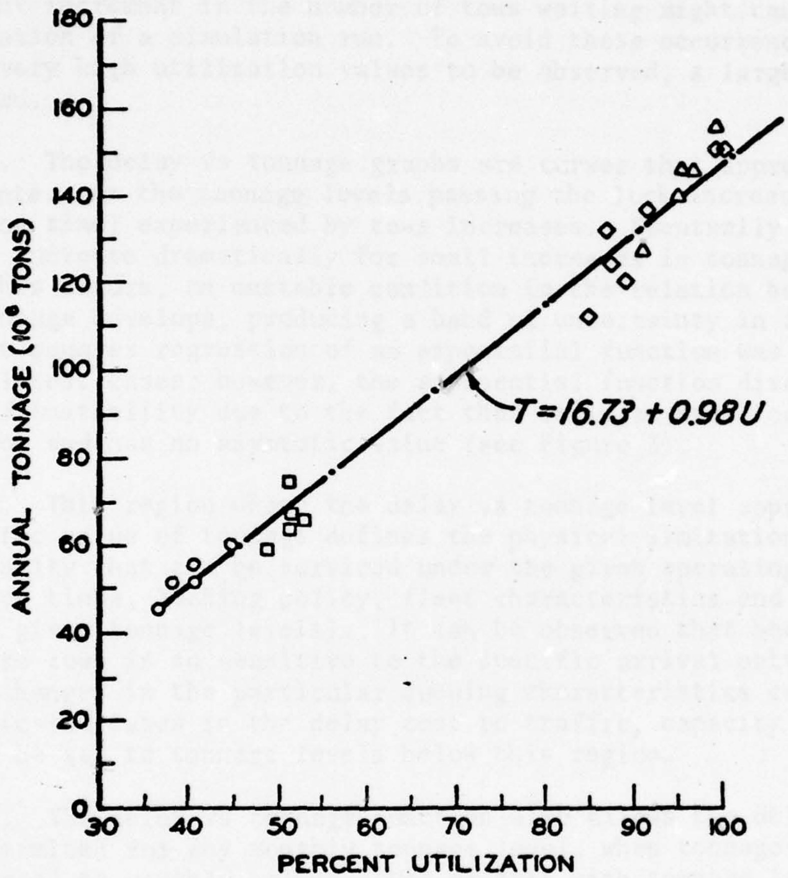


Figure 4. Example of Percent Utilization of Lock Facilities vs Annual Tonnage

44. Some of the runs terminated with "Infinite queuing." This term is applied when the activity (traffic waiting for service) reaches a preset limit. Model runs were made with a queue limit of 50 tows. This value was chosen for several reasons. Fifty tows waiting for service on each side of the lock is considered "limiting" if not "impossible" from a practical standpoint. The model terminates upon reaching this maximum queue length. As in the prototype, the queues are not static, but build and diminish. With a reasonable size queue, a slight increment in the number of tows waiting might cause premature termination of a simulation run. To avoid these occurrences and to allow very high utilization values to be observed, a large number was selected.

45. The delay vs tonnage graphs are curves that approach an asymptote. As the tonnage levels passing the lock increase, the delay (waiting time) experienced by tows increases. Eventually the delay values increase dramatically for small increases in tonnage locked. When this occurs, an unstable condition in the relation between delay and tonnage develops, producing a band of uncertainty in the capacity. A least squares regression of an exponential function was attempted for all test cases; however, the exponential function diverges in the area of instability due to the fact that it is an ever-increasing function and has no asymtotic value (see Figure 3).

46. This region where the delay vs tonnage level approaches an asymtotic value of tonnage defines the physical limitation of tonnage or capacity that can be serviced under the given operating conditions (service times, locking policy, fleet characteristics and commodity mix at given tonnage levels). It can be observed that because the delay to tows is so sensitive to the specific arrival pattern and that small changes in the particular queuing characteristics can cause dramatic increases in the delay cost to traffic, capacity levels should be set to tonnage levels below this region.

47. The delay vs tonnage function also allows the delay cost to be determined for any monthly tonnage level, when tonnages and delays are scaled to monthly values. Use of this with tonnage levels for each month can allow the computation of delay costs accounting for monthly variations in cost.

48. The use of the utilization of the lock facility as a function of tonnage is another way to determine the capacity of a lock. This curve is linear for most cases and once a specific value of utilization is chosen to represent a capacity level of usage, a specific level of tonnage associated with that utilization could be obtained for use in an economic evaluation of alternatives for each lock configuration tested (see Figure 4).

49. With the tonnage/utilization plots, some of the other variables of lock operation can be accounted for by adjusting the utilization and a different capacity value determined. This is necessary because the simulation model used does not account for all factors that must be considered in determining the capacity of a lock facility. Some of the factors not considered by the model are noted here. The simulation package used in this project deals only with tows that are moving barges, whether the barges are empty or full. It does not have any direct means of introducing work or service boats, towboats without barges, or pleasure craft into the simulation. With the use of this curve, a percentage of the utilization can be subtracted to account for the utilization of the lock by these other lock users. Another factor, down-time due to mechanical failures, maintenance or accidents can also be easily compensated for by this type of capacity definition.

RESULTS

Capacity of Present System

50. The present chambers at L&D 26 were tested rather extensively. Several different modes of operation, i.e., locking policies, were modeled (Table 6). The basic difference in modes was the implementation of a ready-to-serve policy discussed previously. These tests will be described here.

51. Following verification, a FIFO mode was tested for various tonnage levels (Tables 7 and 8). Several runs were then made with a change in specific lockage types (singles to setovers) of certain 2 and 3 barge tows in order to determine the impact of the lockage mix. This set of runs, called the Fleet-in-Run-of-River Configuration, showed no significant difference in capacity. In addition, a slight change in the fleet composition to larger tows (Intermediate Fleet Characteristics) did not produce any significant change in capacity (see Figure 5). Next, the locking time distributions of the chambering and long entry components were reduced by 10 percent to model the effect of more efficient locking operation, however this might be accomplished (see Figure 6). This resulted in an increase in capacity of slightly more than 10 percent. A helper boat that assisted the doubles in a similar manner to that tested by PMM&C was tested by using a shorter double lockage time. A resulting increase in capacity of about 21 percent was realized (see Figure 6).

52. Use of the ready-to-serve operating policy produced the most dramatic increase in capacity. It was chosen as the policy to test most rigorously. Several combinations of queue selection were then investigated: FIFO, 1-up; 1-down or flip-flop, 3-up; 3-down.

TABLE 6
PRESENT SITE PRESENT LOCKS
SENSITIVITY ANALYSIS AND OPERATING POLICY COMPARISON
(Million tons/year)

Lock Operating Policy	1972 Fleet Characteristics Most Likely Traffic Level	1972 Fleet Characteristics Modified Traffic Level	Large Fleet Characteristics Most Likely Traffic Level
FIFO (first come-first served)		57-68	
FIFO*		60-67	
FIFO & Helper Boat for Doubles		72-79	
FIFO w/10% Reduction in Operating Times		66-74	
FIFO**		56-65	
Ready to Serve, FIFO	70-79	72-83	78-93
Ready to Serve, FIFO w/10% Reduction in Operating Times		78-86	
Ready to Serve, 1-up; 1-down		72-78	
Ready to Serve, 3-up; 3-down		72-78	

*Fleet in Run of River Configuration
**Intermediate Fleet Characteristics

TABLE 7

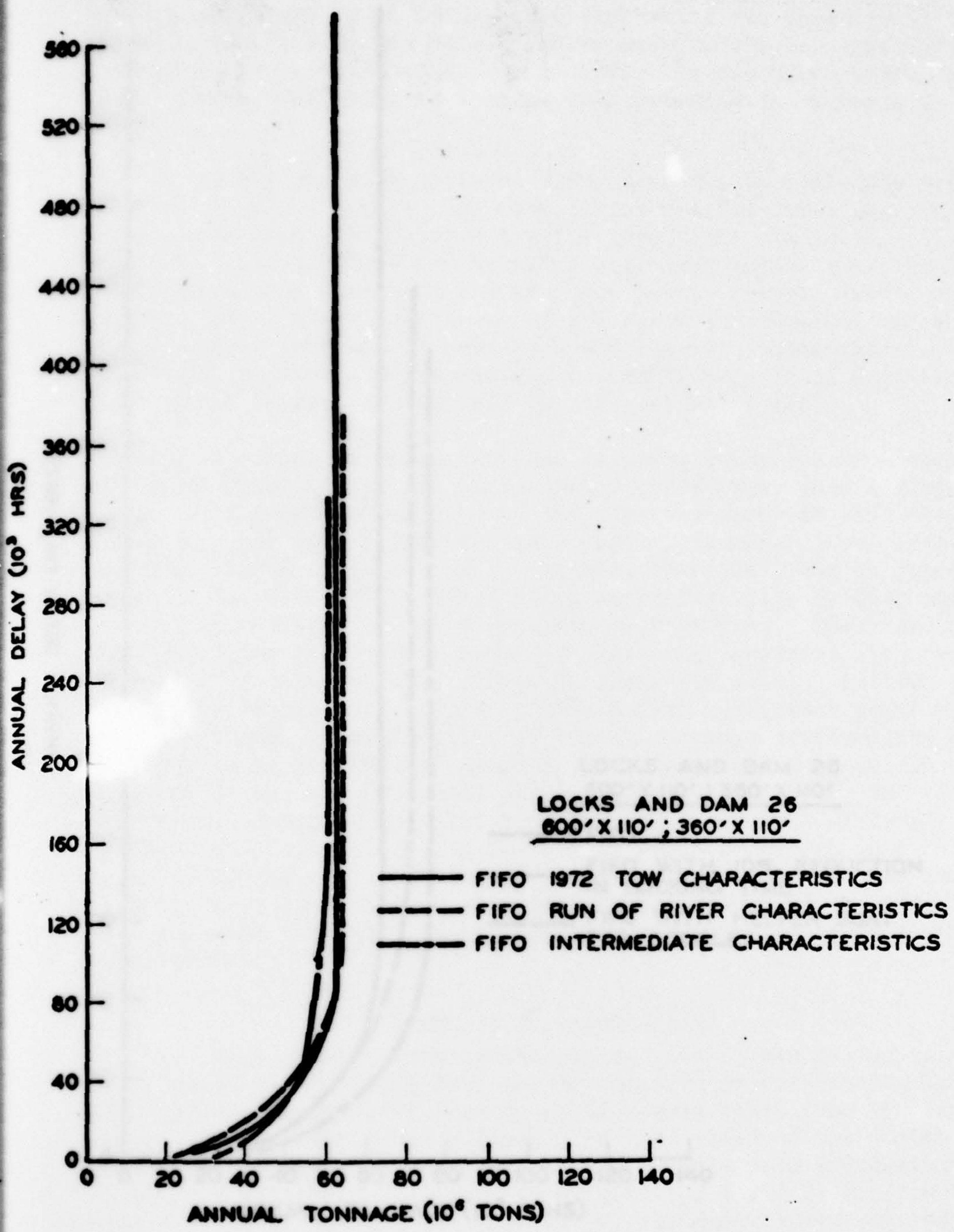
Summary of Projected Waterborne Commerce Through Locks No. 26
Most Likely Traffic Level
1972-2040
(Tons in Thousands)

	1972	1980	1985	1990	2000	2010	2020	2030	2035	2040
Corn	14,977	12,202	13,607	19,594	28,398	31,209	34,504	38,299	40,335	42,082
Soybeans	4,737	7,774	9,867	12,334	15,299	16,981	18,687	20,649	21,677	22,774
Other Grains	2,519	2,030	2,135	2,434	2,805	3,082	3,368	3,738	3,940	4,119
Coal	7,953	11,135	12,676	13,819	16,777	20,144	24,208	29,079	31,870	34,920
Petroleum	8,130	18,838	27,891	31,517	55,411	36,579	38,027	39,928	61,000	42,019
Cement, Stone, Sand & Gravel	1,204	1,109	1,195	1,287	1,494	1,724	2,011	2,322	2,510	2,708
Iron & Steel	1,919	3,183	3,364	3,639	4,286	4,972	5,811	7,002	7,670	8,480
Industrial Chemicals	3,967	5,277	6,200	7,321	10,145	13,973	18,024	23,041	26,005	29,433
Agricultural Chemicals	2,669	4,100	4,513	5,145	5,847	6,490	7,187	7,942	8,331	8,749
Miscellaneous & Other	4,226	4,487	4,856	5,380	6,611	7,244	7,961	8,797	9,378	9,924
TOTAL	52,300	70,135	86,304	102,470	127,073	142,398	159,788	180,797	192,716	205,208

TABLE 8

Summary of Projected Waterborne Commerce Through Locks No. 26
Modified Traffic Level
1972-2040
(Tons in Thousands)

	1972	1980	1985	1990	2000	2010	2020	2030	2035	2040
Corn	14,977	12,202	13,607	19,594	28,398	31,209	34,504	38,299	40,335	42,082
Soybeans	4,737	7,774	9,867	12,334	15,299	16,981	18,687	20,649	21,677	22,774
Other Grains	2,519	2,030	2,135	2,434	2,805	3,082	3,368	3,738	3,940	4,119
Coal	7,953	11,135	12,676	13,819	16,777	20,144	24,208	29,079	31,870	34,920
Petroleum	8,130	18,838	27,891	31,517	55,411	36,579	38,027	39,928	61,000	42,019
Cement, Stone, Sand & Gravel	1,204	1,109	1,195	1,287	1,494	1,724	2,011	2,322	2,510	2,708
Iron & Steel	1,919	3,183	3,364	3,639	4,286	4,972	5,811	7,002	7,670	8,480
Industrial Chemicals	3,967	10,643	6,200	7,321	20,460	13,973	36,350	23,041	26,005	59,360
Agricultural Chemicals	2,669	6,557	4,513	5,145	9,350	6,490	11,493	7,942	8,331	13,991
Miscellaneous & Other	4,226	4,487	4,856	5,380	6,611	7,244	7,961	8,797	9,378	9,924
TOTAL	52,300	77,958	86,304	102,470	140,891	142,398	182,420	180,797	192,716	240,377



. Figure 5. Sensitivity of Capacity to Vessel Characteristics

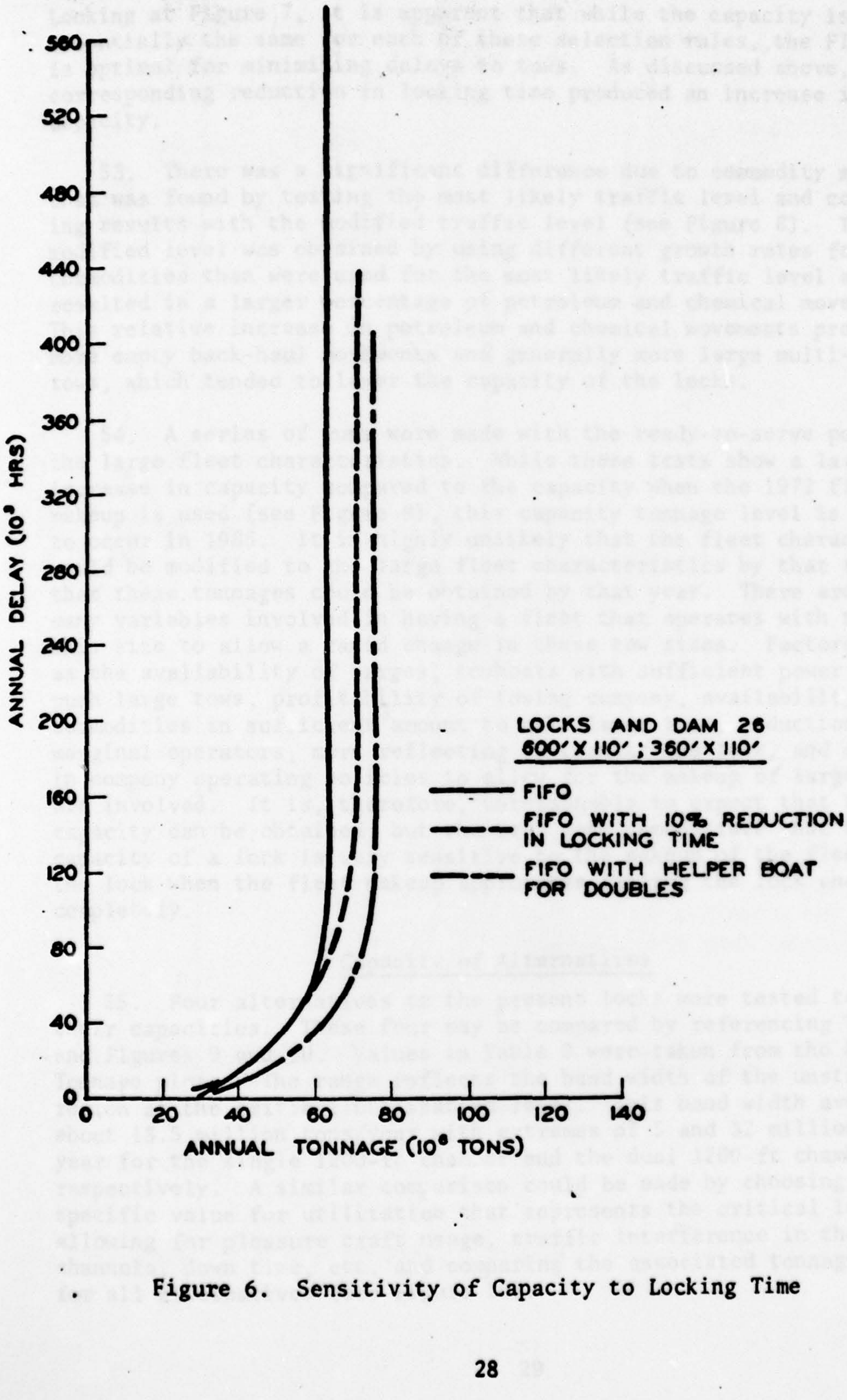


Figure 6. Sensitivity of Capacity to Locking Time

Looking at Figure 7, it is apparent that while the capacity is essentially the same for each of these selection rules, the FIFO case is optimal for minimizing delays to tows. As discussed above, a corresponding reduction in locking time produced an increase in capacity.

53. There was a significant difference due to commodity mix that was found by testing the most likely traffic level and comparing results with the modified traffic level (see Figure 8). The modified level was obtained by using different growth rates for the commodities than were used for the most likely traffic level and resulted in a larger percentage of petroleum and chemical movements. This relative increase in petroleum and chemical movements produced more empty back-haul movements and generally more large multi-cut tows, which tended to lower the capacity of the locks.

54. A series of runs were made with the ready-to-serve policy for the large fleet characteristics. While these tests show a large increase in capacity compared to the capacity when the 1972 fleet makeup is used (see Figure 8), this capacity tonnage level is projected to occur in 1985. It is highly unlikely that the fleet characteristics would be modified to the large fleet characteristics by that time so that these tonnages could be obtained by that year. There are too many variables involved in having a fleet that operates with tows of this size to allow a rapid change in these tow sizes. Factors such as the availability of barges, towboats with sufficient power to push large tows, profitability of towing company, availability of commodities in sufficient amount to make large tows, reduction of marginal operators, more refleeting to transit the lock, and changes in company operating policies to allow for the makeup of larger tows are involved. It is, therefore, unreasonable to expect that this capacity can be obtained; but the test does demonstrate that the capacity of a lock is very sensitive to the makeup of the fleet using the lock when the fleet makeup approaches filling the lock chamber completely.

Capacity of Alternatives

55. Four alternatives to the present locks were tested to determine their capacities. These four may be compared by referencing Table 9 and Figures 9 and 10. Values in Table 9 were taken from the Delay vs Tonnage plots. The range reflects the band width of the unstable region at the critical utilization level. This band width averages about 13.5 million tons/year with extremes of 5 and 32 million tons/year for the single 1200-ft chamber and the dual 1200-ft chambers, respectively. A similar comparison could be made by choosing a specific value for utilization that represents the critical level, allowing for pleasure craft usage, traffic interference in the approach channels, down time, etc. and comparing the associated tonnage levels for all alternatives (see Figure 10).

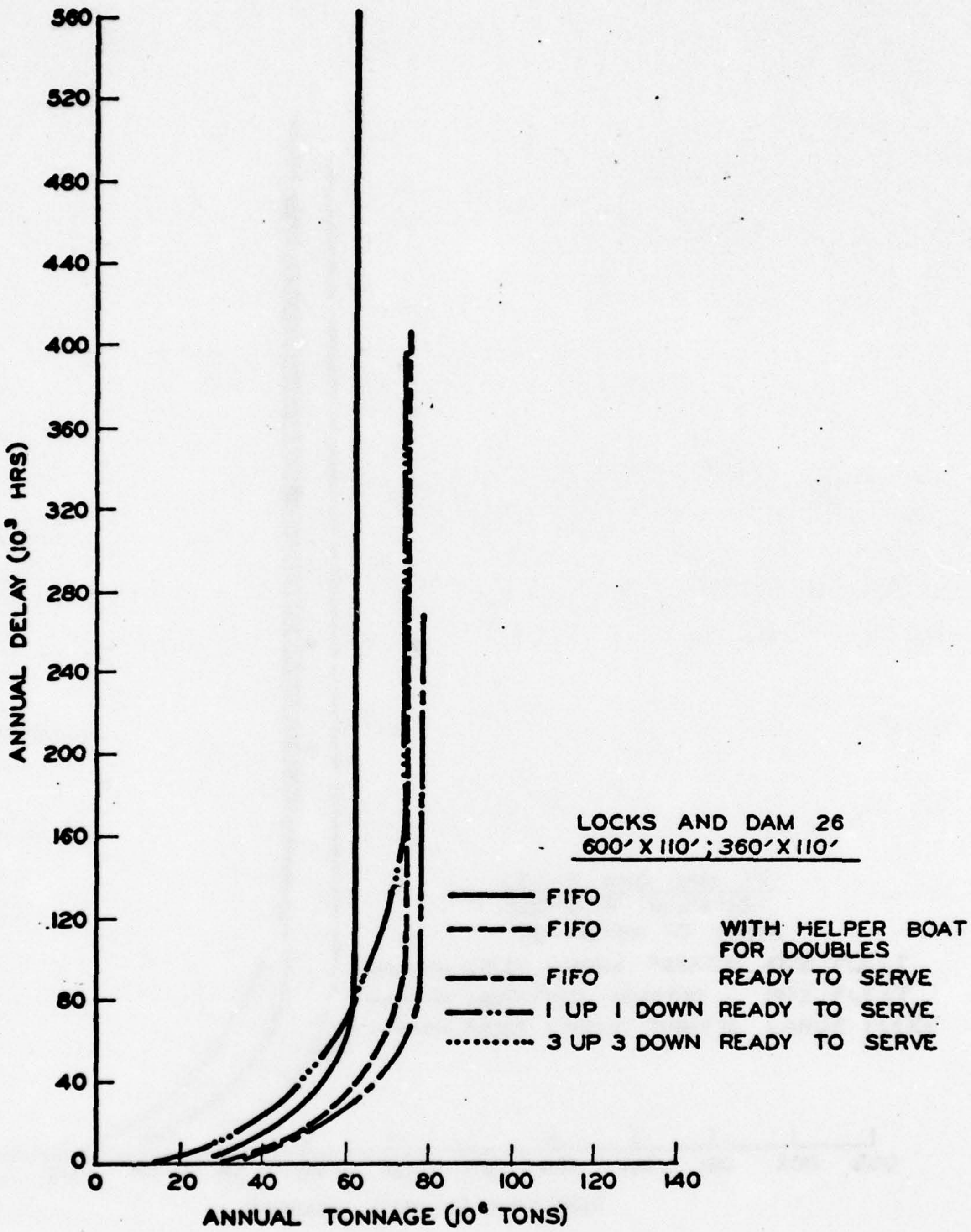


Figure 7. Effect of Ready to Service Policy on Lock Capacity

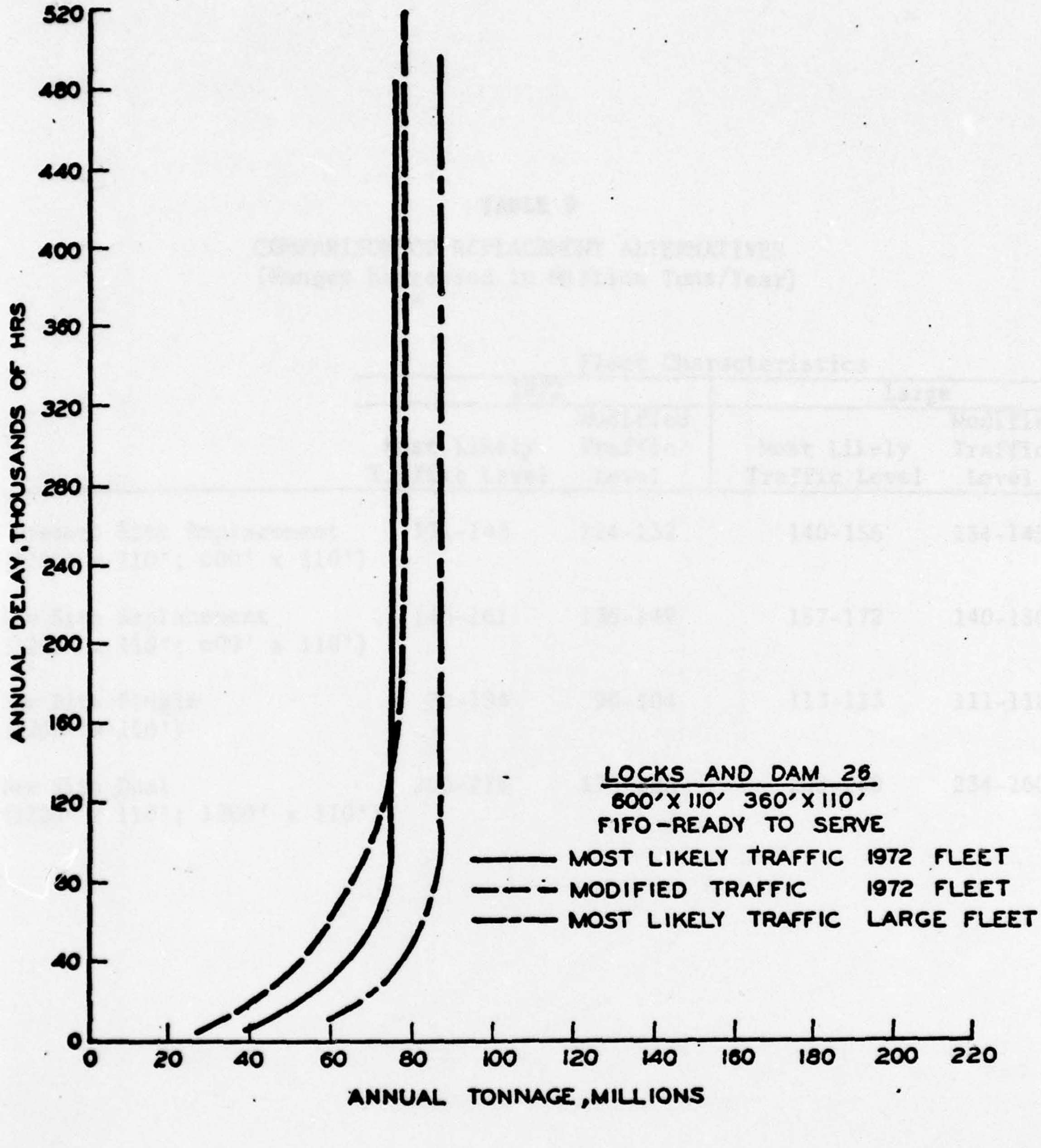


Figure 8. Effect of Traffic Mix on Lock Capacity

TABLE 9

COMPARISON OF REPLACEMENT ALTERNATIVES
(Ranges Expressed in Million Tons/Year)

	Fleet Characteristics			
	1972		Large	
	Most Likely Traffic Level	Modified Traffic Level	Most Likely Traffic Level	Modified Traffic Level
Present Site Replacement (1200' x 110'; 600' x 110')	131-143	124-132	140-156	134-145
New Site Replacement (1200' x 110'; 600' x 110')	146-161	136-149	157-172	140-150
New Site Single (1200' x 110')	90-104	90-104	113-123	111-118
New Site Dual (1200' x 110'; 1200' x 110')	200-215	173-188	208-240	234-260

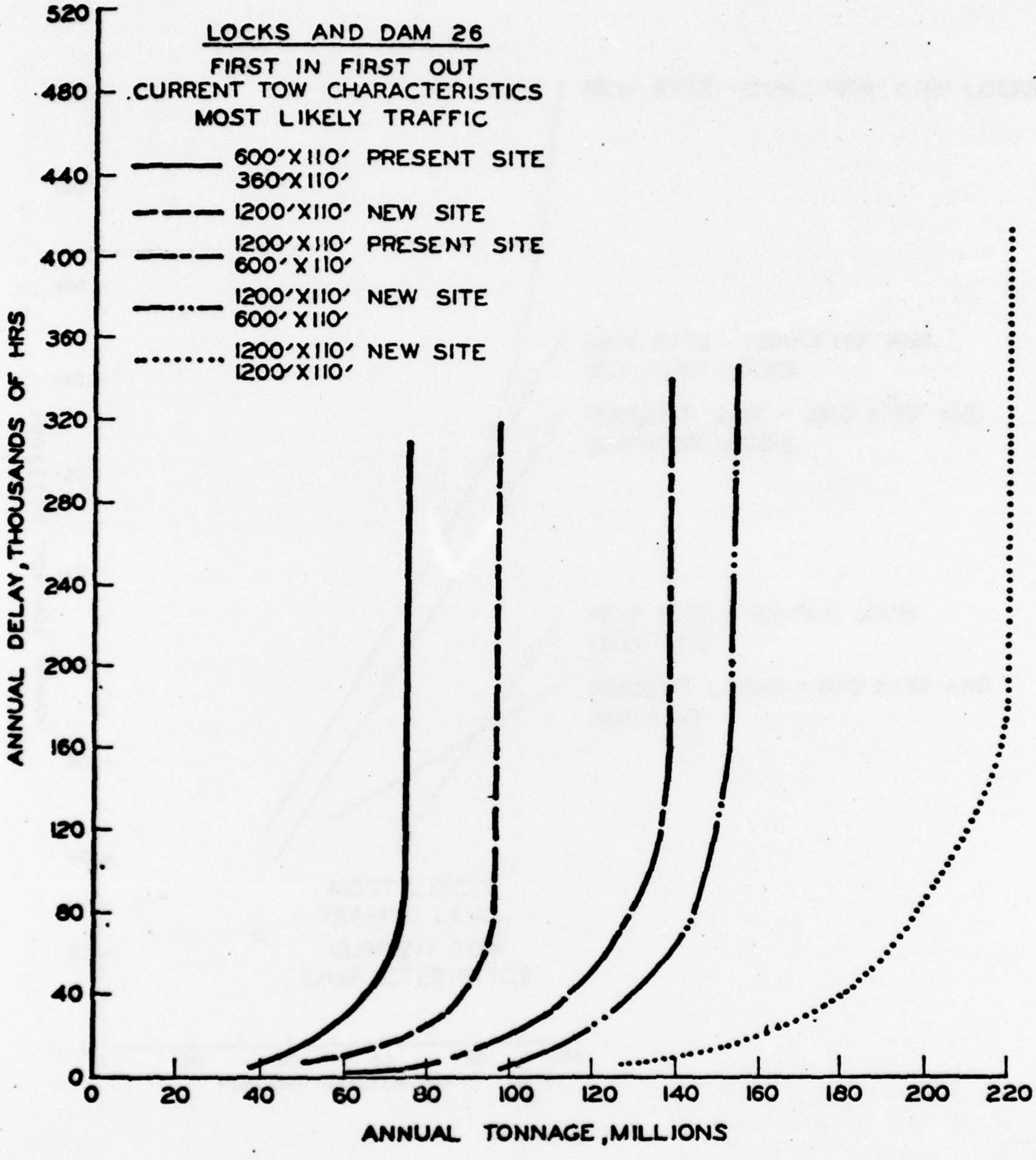


Figure 9. Analysis of Alternative Replacement Lock Capacities

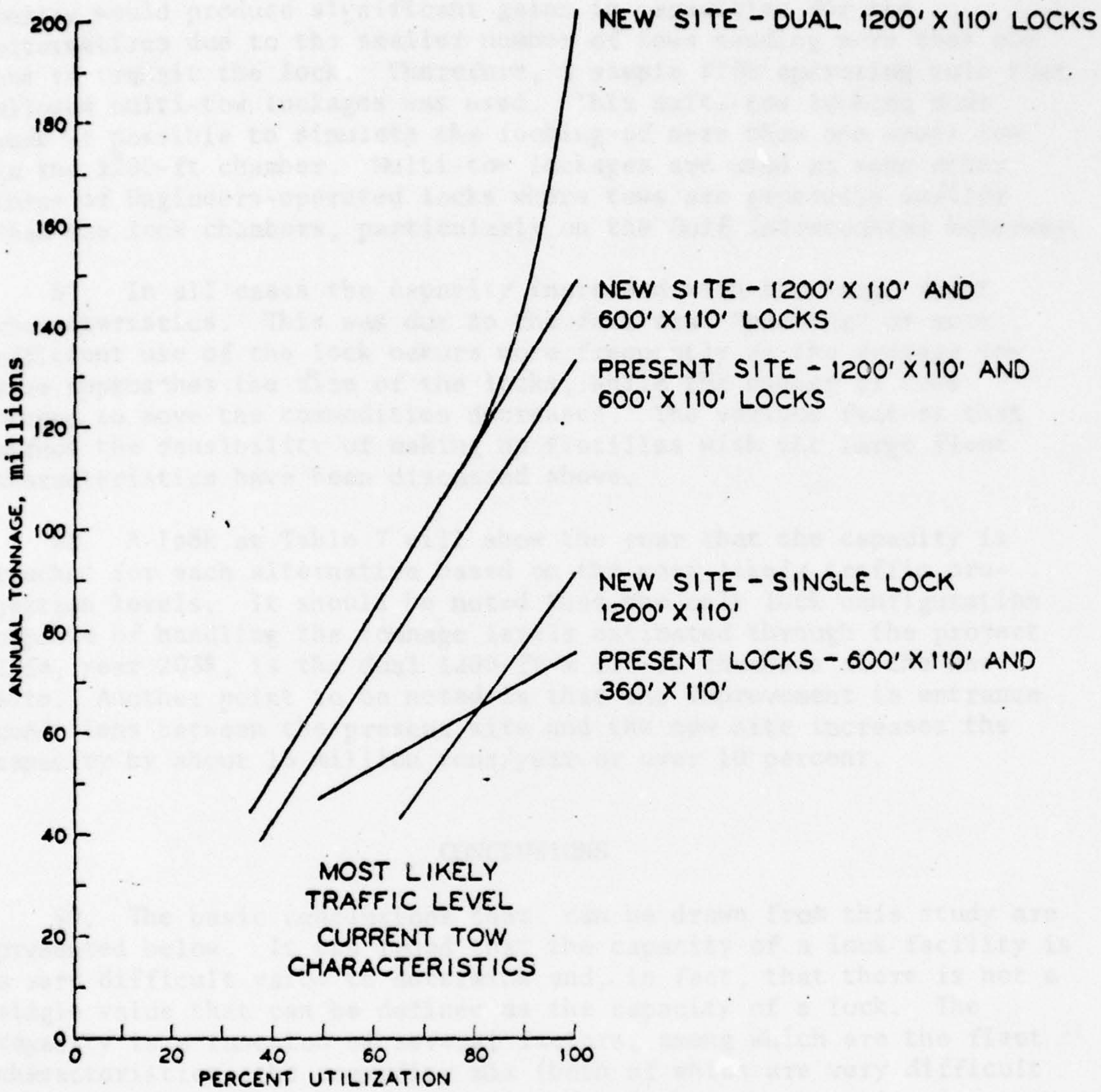


Figure 10. Analysis of Alternative Replacements for L&D 26 Using WATSIM

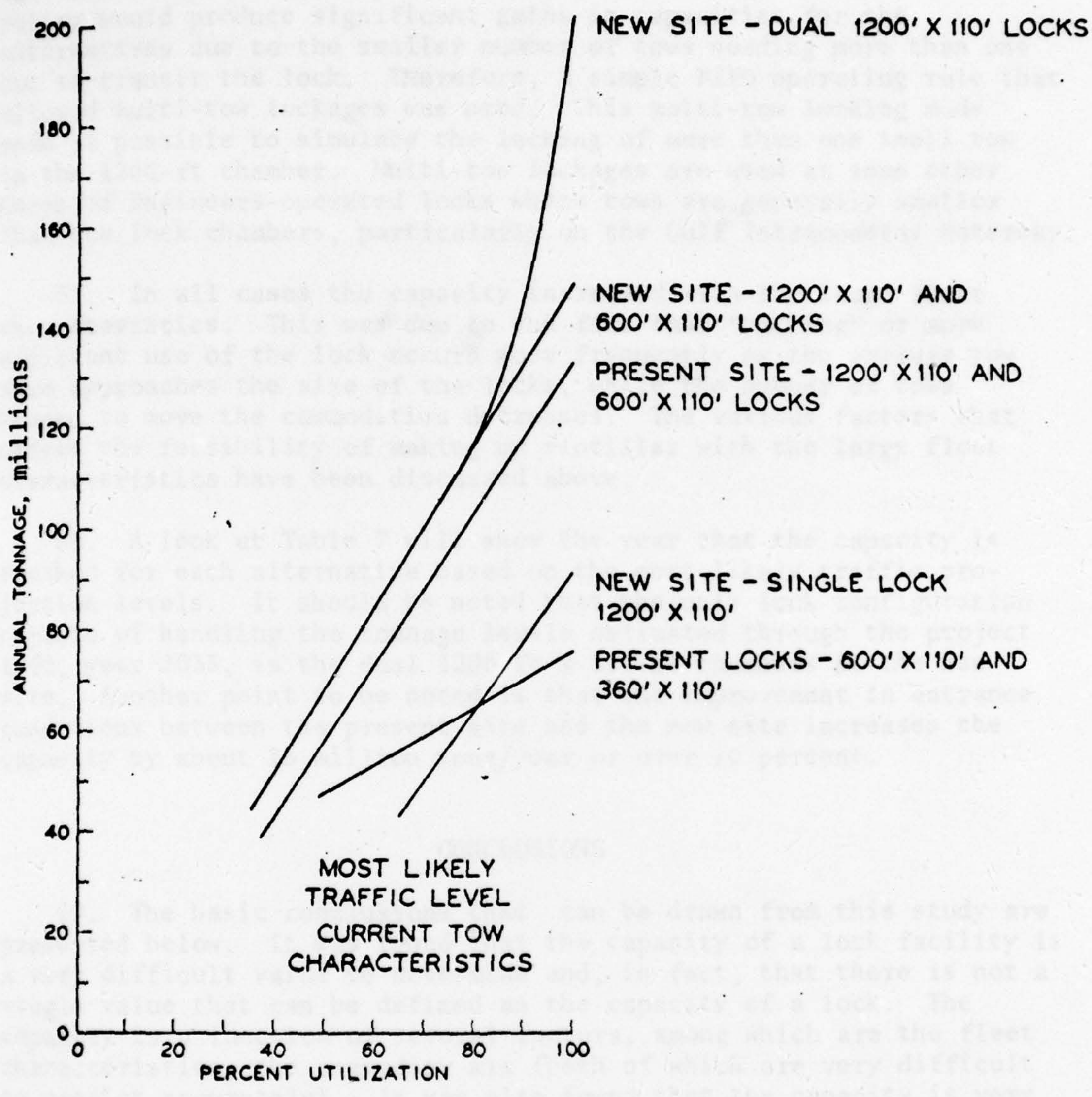


Figure 10. Analysis of Alternative Replacements for L&D 26 Using WATSIM

56. It is appropriate to discuss the operating policy used for testing the capacity of the alternatives. While the question of the present locks was to find a maximum capacity using whatever nonstructural methods that would be reasonable (which resulted in the use of a ready-to-serve operating rule) it is unlikely that this policy would produce significant gains in capacities for the alternatives due to the smaller number of tows needing more than one cut to transit the lock. Therefore, a simple FIFO operating rule that allowed multi-tow lockages was used. This multi-tow locking mode made it possible to simulate the locking of more than one small tow in the 1200-ft chamber. Multi-tow lockages are used at some other Corps of Engineers-operated locks where tows are generally smaller than the lock chambers, particularly on the Gulf Intracoastal Waterway.

57. In all cases the capacity increased with the large fleet characteristics. This was due to the fact that "packing" or more efficient use of the lock occurs more frequently as the average tow size approaches the size of the locks, while the number of tows needed to move the commodities decreases. The various factors that affect the feasibility of making up flotillas with the large fleet characteristics have been discussed above.

58. A look at Table 7 will show the year that the capacity is reached for each alternative based on the most likely traffic projection levels. It should be noted that the only lock configuration capable of handling the tonnage levels estimated through the project life, year 2035, is the dual 1200-ft x 110-ft chambers at the new site. Another point to be noted is that the improvement in entrance conditions between the present site and the new site increases the capacity by about 15 million tons/year or over 10 percent.

CONCLUSIONS

59. The basic conclusions that can be drawn from this study are presented below. It was found that the capacity of a lock facility is a very difficult value to determine and, in fact, that there is not a single value that can be defined as the capacity of a lock. The capacity is a function of several factors, among which are the fleet characteristics, the commodity mix (both of which are very difficult to predict accurately). It was also found that the capacity is very sensitive to the time required for locking. However, using the conditions considered most likely to exist, it is possible to determine reasonable estimates of the capacity of locks and even the increases in capacity that may be obtained through nonstructural improvements.

LITERATURE CITED

1. Transportation Association of America, Transportation Facts and Trends, 10th Edition, October 1973, p 8.

2. Bottoms, Eric E., "Practical Tonnage Capacity of Canalized Waterways," Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, VOL 92, February 1966, pp 33-47.

3. Davis, John P., "Tonnage Capacity of Locks," Journal of the Waterways and Harbors Division, Proceedings of the American Societ yof Civil Engineers, VOL 95, May 1969, pp 201-213.

4. Carroll, Joseph L., Capacity of a Waterway Lock via Simulation, Occasional Paper No. 6, Center for Research of the College of Business Administration, The Pennsylvania State University, 1968.

5. Bronzini, M. S., Waterways Systems Simulation: TOWGEN: A Tow Generation Model for Inland Waterway Simulation, VOL III, August 1971, Pennsylvania Transportation and Traffic Safety Center, University Park, PA.

6. Daggett, L. L., Ankeny, T. D., and Eiland, J. A., A New Generalized Waterway Simulator: WATSIM IV, U. S. Army Engineers Waterways Experiment Station, to be published.

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Daggett, Larry L
Determination of lock capacities using simulation modeling, by Larry L. Daggett [and] Thomas D. Ankeny. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.
36 p. illus. 27 cm. (U. S. Waterways Experiment Station. Miscellaneous paper H-75-9)
Prepared for U. S. Army Engineer District, St. Louis, St. Louis, Missouri.
Literature cited: p. 36.

1. Computerized simulation. 2. Inland waterways. 3. Locks and Dam 26, Mississippi River. 4. Locks (Waterways). I. Ankeny, Thomas D., joint author. II. U. S. Army Engineer District, St. Louis. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper H-75-9)
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